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by Paul Moy, Tusit Weerasooriya, Thomas F. Juliano, Mark R. VanLandingham, and Wayne Chen

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14. ABSTRACT
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15. SUBJECT TERMS
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Recent work on formulating alternatives to ballistic gelatin, a soft tissue simulant, has lead to the development of physically associating gels (PAG). Ballistic gelatin impact response has been traditionally used to test and evaluate firearms and bullets but it does have some drawbacks, such as lacking consistency in its viscoelastic properties due to variability during the fabrication process, short shelf-life, and deterioration under prolonged usage at room temperature. PAG offers advantages such as the ability to tailor desired properties, a narrow range of viscoelastic properties, storage at room temperature, and superior environmental stability compared to ballistic gelatin. However, like ballistic gelatin, the material response and failure behavior at high rates are still not completely understood. High rate (~2500/s) compression experiments were conducted on ballistic gelatin and two types of PAG using a modified split-Hopkinson bar under dynamic equilibrium at constant strain rates using a pulse-shaping technique. Aside from these experimental conditions, considerations have been taken regarding the radial inertia effects that are typically observed during Hopkinson bar experiments of compliant materials such as gels. In addition to high rate experiments, stress-strain behavior of these materials at an intermediate strain-rate (1/s) was also obtained. In this paper, the test methodology used for the split-Hopkinson bar experiments is discussed, and the stress-strain behavior of ballistic gelatin and PAG are presented and compared.

INTRODUCTION
For decades, the impact response of ballistic gelatin has been widely used for testing and evaluating firearms and bullets. Although this tissue simulant has the approximate density and viscosity of living tissues, it significantly lacks the structure of normal human tissues, i.e. fibrous muscle tissues, internal organs, and fat [1]. Other downsides with ballistic gelatin are that the material must be stored around 10^{o}C and decomposition of the hydrated gelatin begins after just a few days [2]. However, ballistic gelatin does provide a qualitative insight of the bullet penetration and interaction into soft tissue. These studies range from the bullet trajectory path, depth of penetration, temporary and permanent cavity wounds, and bullet fragmentation, if any.

Recent work at the US Army Research Laboratory has lead to the development of alternatives to ballistic gelatin, including physically associating gels (PAGs). PAGs offer advantages such as the ability to tailor a desired mechanical response, a narrow range of viscoelastic properties, and superior environmental stability compared to ballistic gelatin. However, like ballistic gelatin, the material response and failure behavior at high rates are still not completely understood.

One technique to study materials under dynamic loading and high strain-rate deformation is commonly known as the split-Hopkinson pressure bar (SHPB) method, sometimes also known as the Kolsky bar method [3]. For example, Weerasooriya [4] and Green et al [5] each studied the compression behavior affected by a low-to-high strain rate response for tungsten alloys on a maraging steel split-Hopkinson bar. Maiden and Green [6] used the SHPB to determine the dynamic compressive stress-strain behavior of Lucite and Micarta. Chou *et al.* [7] also measured the compressive behavior of plastics using similar methods, and Briscoe and Nosker [8] determined the rate effects on the flow stress of high-density polyethylene. Both works have indicated that the yield strength of materials tested increases with strain rate. In more recent work, Moy *et al.* [9, 10] and Chen *et al.* [11, 12] used a modified aluminum SHPB to study thermoplastics under high strain rate compression and uniaxial tension conditions.

However, the testing of extremely compliant materials at high rates using the split Hopkinson bar has many challenges. During high loading rates, the specimen should be under dynamic stress equilibrium (loads applied at a given time on both sides of the specimen should be approximately the same) and deform uniformly for nearly the entire duration of the experiment. During deformation, the strain rate must be nearly constant as it is a controlled variable. Further, a modified specimen geometry and other methods are needed to reduce radial inertia effects and transmitted signals from strain gages must be properly amplified as their magnitudes are small. These issues are addressed and explained later in the following sections. During high rate experiments, an emphasis was placed on maintaining the validity of the experimental results. Stress-strain behavior from high rate and some intermediate rate experiments for ballistic gelatin and PAGs, are presented and compared in this paper.

MATERIAL

Ballistic Gelatin

Ballistic gelatin samples were made from a 20% by mass 250 bloom type A ordnance gelatin (acquired from GELITA USA Inc., Sioux City, IA) with 40^{o}C ultra-pure filtered water. The mixture was stirred slowly with a mixer to dissolve all the particles and to minimize air bubbles. After, the solution was poured into aluminum molds to form a right cylindrical specimen. Two different sets of molds were used for intermediate and high rate experiments. For the intermediate specimens, both the diameter and length were 12.7 mm. Specimen geometry for the Hopkinson bar was 12.7 mm in diameter and 1.45 mm in length. Ballistic gelatin requires a storage temperature of approximately 10^{o}C. Typically, ballistic gelatin was made when experiments were ready to be carried out the following day. It is known that gelatin begins to degrade over a period of one week even when stored at the recommended temperature.

Physically Associating Gelatin

In the preliminary development of an advanced tissue simulant, two types of PAG were created. The PAGs are formulated from commercially available triblock copolymers consisting of polystyrene (PS) and polyisoprene (PI). Both consist of an 80% mass fraction triblock (PS-PI-PS) and 20% mass fraction diblock (PS-PI) composition. One of the associating gels contains 15% by mass PS (identified as PAG15) and the other gel contains 30% by mass PS (PAG30). The final gel contained by volume 20% polymer and 80% mineral oil, which was used as the solvent. The solution was placed in a nitrogen-purged vacuum oven at ~150ºC and fully dissolved over a period of about 6 hours, being stirred every hour. Unlike the casting of the ballistic gelatin, the melt solution was poured into pre-heated aluminum molds. This extended the time for gelation of the PAG, thus allowing the PAG solution to fill the mold to the desired shape. Two specimen geometries were used with dimensions equal to that for the ballistic gelatin.

INTERMEDIATE RATE EXPERIMENTS

Uniaxial compression experiments were conducted at a constant strain rate of 1/s on a servo-hydraulic Instron test machine. A computer program was written to command an exponentially decaying reference input voltage from a WaveTek signal function generator to the Instron control unit to achieve the constant true strain rate. Oil was used as a lubricant on the specimen ends to minimize friction between the compression platens and specimens. To further mitigate the friction, the aluminum compression platens were polished to a mirror-like finish, to assuage the intrinsic tackiness of the PAG specimens.

HIGH RATE EXPERIMENTS

Generally, a conventional SHPB consists of a striker, an incident bar (input), and a transmission bar (output). The working principles of such a setup are well documented [13, 14]. Assuming the specimen undergoes homogenous deformation and the incident and transmission bars are of the same diameter and material, the analysis based on one-dimensional wave theory [3] shows that the nominal strain rate, $\dot{\varepsilon}(t)$, in the specimen to be

$$\dot{\varepsilon}(t) = -\frac{2c_{\circ}}{L}\varepsilon_r(t)\,, \qquad (1)$$

where L is the original gage length of the specimen, $\varepsilon_r(t)$ is the time-resolved strain associated with the reflected pulse in the incident bar, and $c_{\circ}$ is the elastic bar-wave velocity of the bar material. Integration of equation (1) with respect to time gives the time-resolved axial strain of the specimen. The nominal axial stress, σ, in the specimen is determined using the equation

$$\sigma(t) = \frac{A_t}{A_s} E_t \varepsilon_t(t) , \qquad (2)$$

where A_s is the cross-sectional area of the specimen, $\varepsilon_t(t)$ is the time-resolved axial strain in the transmission bar of cross-sectional area, A_t, and Young's modulus, E_t.

However, the ability of the Hopkinson bar apparatus to obtain a considerable stress response for soft materials such as gels or gelatin is limited due to a high noise to signal ratio in the transmission bar. The generated incident pulse traveling through a low impedance material is reduced by several orders of magnitude in a metal output bar, in comparison to a specimen with a higher sound velocity such as a metal alloy. Moy *et al.* [9, 10] and Chen *et al*. [11, 12, 15] used a 19-mm diameter 7075 aluminum SHPB bar with a pulse-shaping technique to study the dynamic response of thermoplastics. The aluminum bars amplify the strain signals to some extent, thus the signal to noise ratio is low and the pulse shaping technique ensures that the equilibrium stress state and homogenous deformation in the polymer has been reached before failure or yielding occurred. For extremely compliant materials, these methods still do not suffice. To overcome this issue, semi-conductor strain gages were used in place of common resistive foil-type strain gages on the input and output bars. The semi-conductor gages have sensitivity 50-75 times greater than that of traditional foil gages. The semi-conductor gages are bonded at the midpoint on the surface of the aluminum input and output bars and the electrical circuitry is completed through a Wheatstone bridge. Figure 1 shows the comparison of the output signals from semi-conductor gages and common strain gages. The magnitude of the semi-conductor gage signal is approximately 50 times greater than that from the resistive strain gages, which barely register any signal. The lengths of the input and output bars were 2.4384 m and 1.2192 m, respectively.

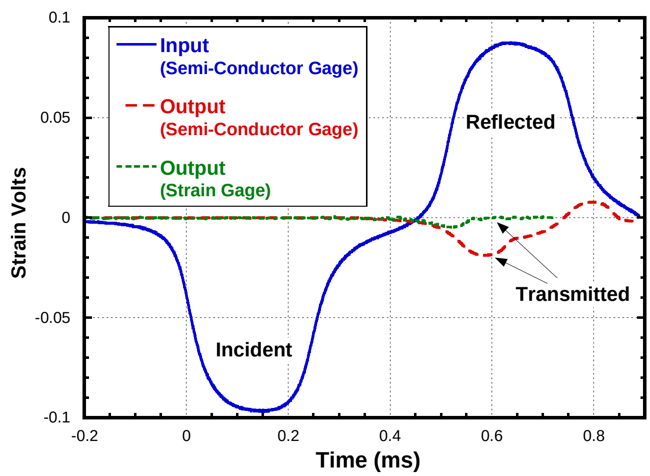


Figure 1: Oscilloscope traces for the sensitivity comparison of semi-conductor strain gages and foil-type resistive strain gages.

For a SHPB experiment to be valid when testing soft materials, the specimen should be in dynamic equilibrium. In addition, during the experiment, a near constant strain rate is required. These are accomplished by wave-shaping the incident pulse and having the proper specimen gage length. Gel specimens were fabricated with a thickness of 1.45 mm for its gage length. High-density insulation foam was used as the pulse shaper and placed at the front face of the incident bar where the striker impacts. Viscous vacuum grease was used to temporarily hold the pulse shaper on the input bar impact face. Without proper pulse-shaping, the rise time for the gel material would not be sufficient for the specimen to reach dynamic stress equilibrium. A 609.6 mm long striker provided the necessary loading pulse for the gel specimens.

In our high rate experiments, a set of quartz force transducers were embedded in the input and output bars. A schematic of the SPHB setup for the ballistic gelatin and PAG compression experiments is shown in Figure 2. Details of the application and technique of the embedded quartz gages for the split-Hopkinson bars are explained by Casem *et al.* [16, 17] and Chen *et al.* [18]. As noted by Casem *et al.*, the signal from the input quartz gage includes an inertial component, in addition to the force applied on the specimen. Casem *et al.* proposed a method to correct the measured signal by subtracting the inertial effect by obtaining the acceleration of the input bar via differentiation of the interface velocity, which was determined by a series of standard strain gages [16, 17]. Figure

3 shows the stress history for ballistic gel from both input bar (1) and output bar (2) quartz gages, the semiconductor gage from the output bar, and the derived stress from the input bar quartz gage with the inertial correction. The data from the corrected quartz gage agrees well with the data from the other quartz gage at the output bar as well as the stress measured by the semiconductor strain gage on the output bar. The purpose for the use of the quartz transducers is to provide immediate dynamic stress of the specimen at the bar-specimen interfaces without analysis of semi-conductor strain gages. The quartz gage signals show whether the experiment is in dynamic equilibrium by directly measuring the stresses at the two loading faces of the specimen. Similar to the Instron compression experiments, oil was used as a lubricant between the loading platens and the specimen for high rate tests. Since these gel materials are very compliant, it was important not to apply any preload on the specimen. Therefore, when installing the specimen, a temporary spacer of the same thickness as the specimen was placed at the outer edge in between the input and output bars. The spacer was removed just prior to testing.

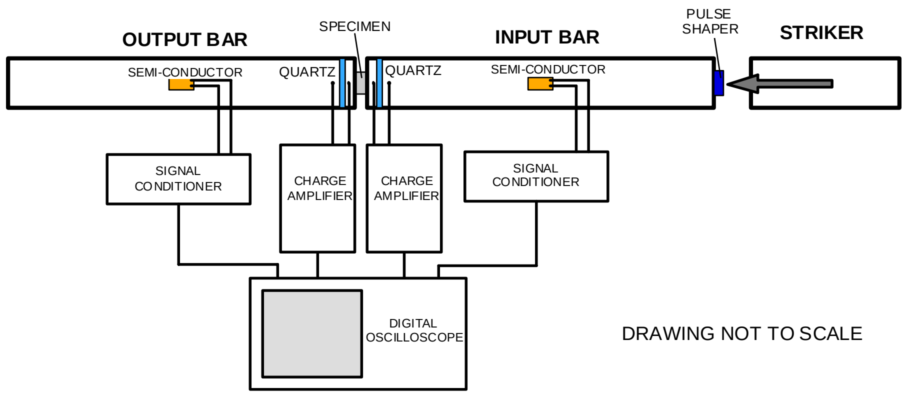


Figure 2: Schematic of pulsed-shaped SHPB set-up with embedded quartz gages.

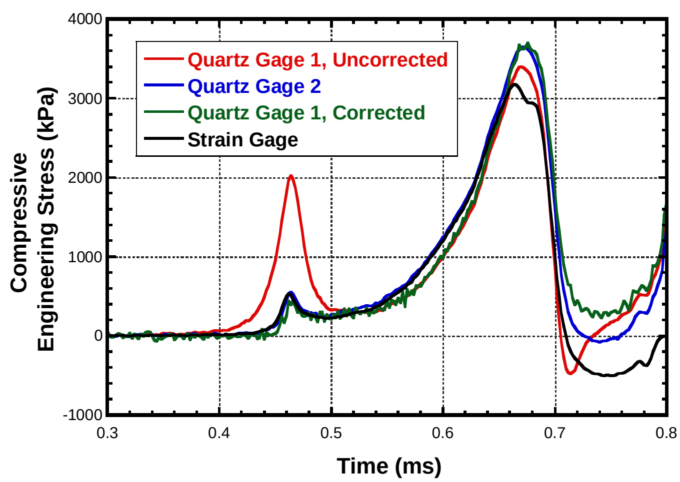


Figure 3: Stress histories of the quartz gages, output bar semiconductor gage, and the corrected input bar quartz trace removing the inertial effects.

Even after the inertial correction, signals still showed a spike at the beginning of the trace for gelatin experiments at high rates. Recent work at high rates by Chen *et al.* on rubber-like gelatin material also showed an initial spike on the stress-strain traces [18]. They determined that these spikes are an experimental artifact during the initial acceleration of the axial strain and not an intrinsic material response. To eliminate this artifact, they proposed to alter the specimen geometry from a right cylinder to an annular shape ring. Following this recommendation, the specimen geometry of 12.7 mm outside diameter and 5.33 mm inside diameter was used in our experiments. Figure 4 shows the comparison of the transmitted pulses for ballistic gelatin between an annular ring and cylindrical specimen. This figure shows that the radial inertial effects are eliminated using the annular shaped ring

specimen. Using these experimental methods, stress-strain behavior of ballistic gelatin and two PAG gels were obtained.

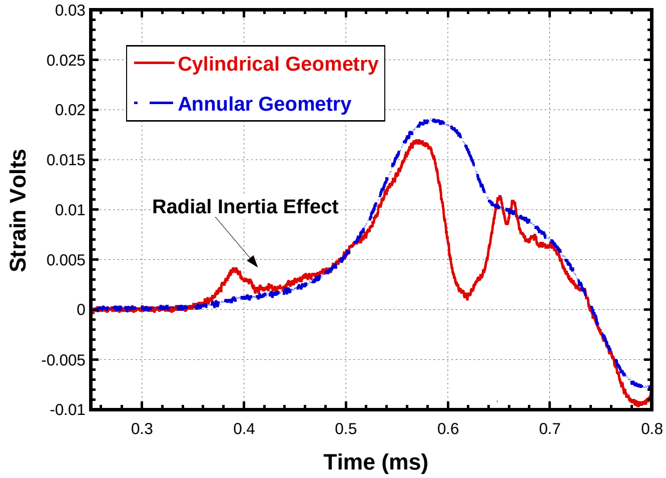
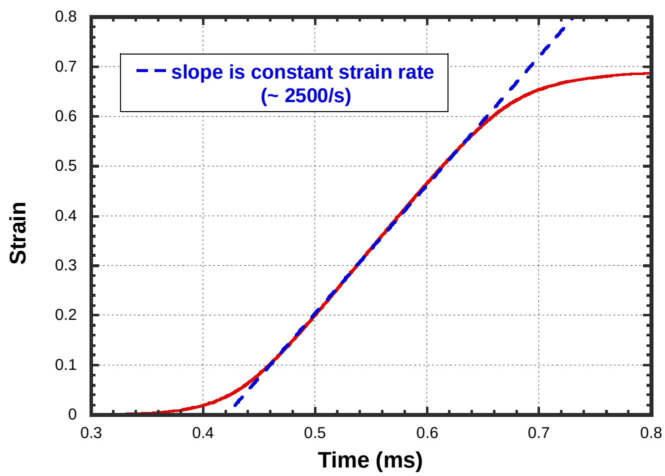


Figure 4: Radial inertial effects of ballistic gelatin.

RESULTS AND DISCUSSION

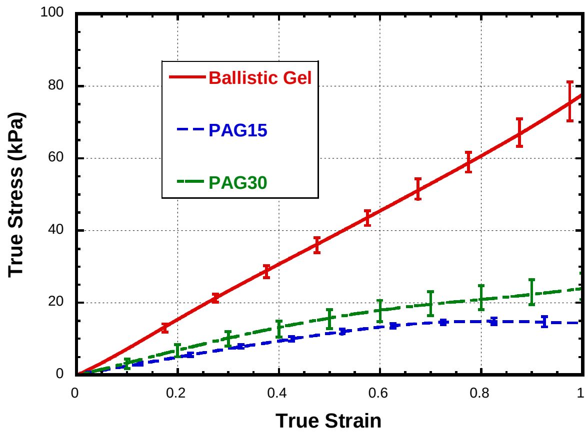
Figure 5 shows a typical strain-time plot for a PAG15 sample from a SHPB experiment, reaching a constant strain rate. Therefore, the high rate experiment for the gel is considered to be valid. All the high rate experiments reached a strain rate of approximately ~2500/s.

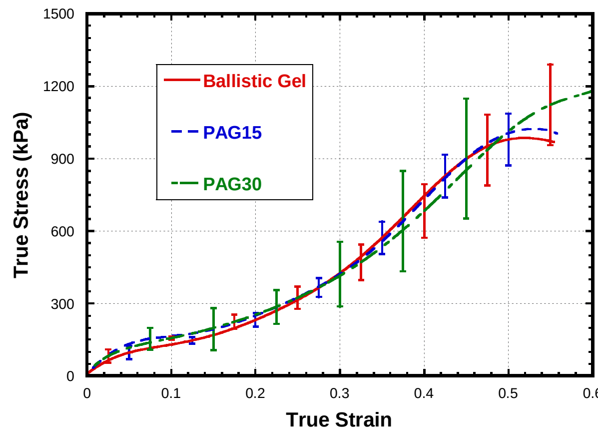


Figures 5: Strain-time plot indicating a near constant strain rate.

Figures 6(a) and 6(b) illustrate the typical stress-strain response for the gels at 1/s and ~2500/s strain rates, respectively. All the data from different specimens lied within the shown error bars. At the intermediate rate of 1/s, the flow stress of the ballistic gelatin is significantly higher than that obtained for the other two PAGs. In addition, the ballistic gelatin has a linear behavior up to about a strain of 1, the maximum strain of the intermediate strain rate experiments. On the other hand, stress-strain response of both PAG15 and PAG30 is non-linear and starts to reach a maximum stress. The ballistic gelatin and PAGs regain their original shape upon unloading even when the specimens are strained to 1, showing a non-linear elastic behavior.

In contrast, the stress-strain response at the high rate is quite different from that observed at 1/s for the three materials. At the high rate, stress-strain responses of all three materials are approximately similar. This indicates that the PAG gels are much more rate sensitive, compared to the ballistic gelatin. As shown in Fig. 6b, the PAG15 gel behaves almost like the ballistic gel, at the high strain rate of ~2500/s.





(a) (b)

Figure 6: Summary of the stress-strain response for ballistic gelatin, PAG15 and PAG30 at (a) 1/s and (b) ~2500/s.

Figure 7 shows the flow stress as a function of strain rate at different strains for all materials investigated. PAGs have higher rate sensitivity than the ballistic gelatin, and the difference in the rate sensitivity increases with strain. This is an important observation, which will influence the penetration behavior of these three materials. During penetration, ballistic gelatin and PAG are deformed and fail under high rates. All three materials seem to have an almost identical deformation behavior at high rates. However, ballistic gelatin and PAG deform differently at low rates. It is expected then that they will deform differently away from the penetration-target interaction zone. At this time, we do not understand how that will influence the penetration behavior of the ballistic gelatin and PAG. Only a computer simulation, taken into account the observed constitutive and failure behavior of these materials, could provide an insight to this.

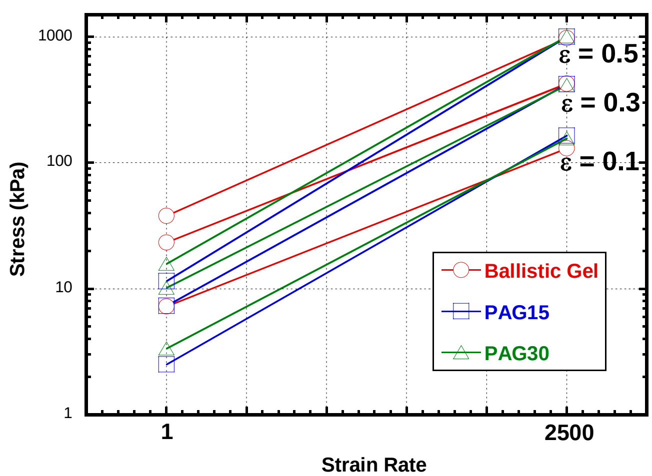


Figure 7: Rate sensitivity of ballistic gelatin, PAG15 and PAG30.

CONCLUSION

The stress-strain responses for ballistic gelatin and PAG at strain rates of 1/s and ~2500/s has been determined under uniaxial compression. Results reveal that the ballistic gelatin has a flow stress that is significantly greater than the PAGs at strain rates of 1/s. However, PAG15 and PAG30 are much more rate sensitive between 1/s and ~2500/s strain rates than the ballistic gelatin. In fact, the stress-strain response of the PAGs was much like the ballistic gelatin under high rate loading conditions. This shows that these alternative tissue simulants corresponds well to the deformation behavior of ballistic gelatin subjected to high strains at high loading rates.

Through the use of semi-conductor strain gages over conventional resistive foil strain gages on the Hopkinson bars, the signal to noise ratio is increased by 50 times, thus allowing the amplification of the transmitted pulses to obtain the stress history in the soft-material specimen. To further validate the SHPB experiments, dynamic stress

equilibrium was achieved by wave-shaping the incident pulse and reducing the specimen gage length. Radial inertial effects were reduced by modifying the specimen geometry from a right cylinder to an annular ring.

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